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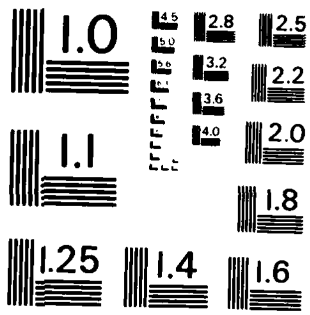
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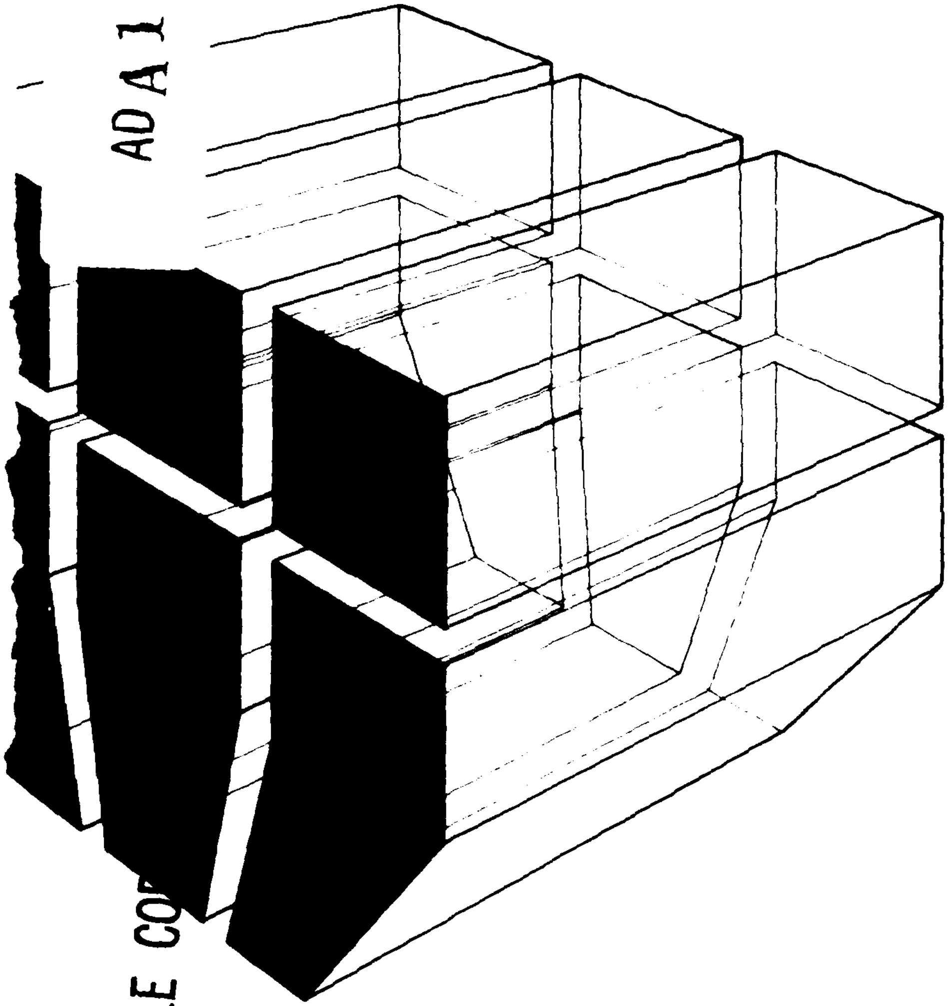
TECHNICAL REPORT N-153
June 1983
Training Area Environmental Impact Prediction

FEASIBILITY OF USING RATIONAL THRESHOLD VALUES TO PREDICT SEDIMENT IMPACTS FROM ARMY TRAINING



by
Caryn C. Vaughn
Gary D. Schnell
Robert E. Riggins

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This report summarizes research on the feasibility of using Rational Threshold Values (RTVs) to predict sediment-related impacts in Army training areas. The information will be useful to Army land managers who program training area maintenance.

The research has indicated that local water quality standards can be used as RTVs if they are based on the aquatic community's response to the physico-chemical and volumetric characteristics of sediment pollution in a specific area. The Relative Algal

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Growth Index, with modifications, can also be used as an RTV for lentic systems. In lotic systems, fish population levels can be used as RTVs for certain fish species if specific criteria are met.

FOREWORD

This study was performed for the Assistant Chief of Engineers under Project 4A762720A896, "Environmental Quality For Construction and Operation of Military Facilities"; Task A, "Installation Environmental Management"; Work Unit 026, "Training Area Environmental Impact Prediction." Mr. Donald Bandel, DAEN-ZCF-B, was the Technical Monitor.

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Dr. R.K. Jain is Chief of CERL-EN. COL Louis J. Circeo is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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FEASIBILITY OF USING RATIONAL THRESHOLD VALUES TO PREDICT SEDIMENT IMPACTS FROM ARMY TRAINING

1 INTRODUCTION

Background

Sediment transported by water is a major cause of degradation to the environment around training ranges and maneuver areas. Sediment becomes a pollutant when it fills reservoirs, lakes, and ponds, clogs stream channels, destroys aquatic habitat, settles on productive land, degrades water quality, increases water treatment costs, damages water distribution systems, and detracts from recreational water use.[1]* Army land managers who program training area maintenance need prediction techniques that include an effective means of indicating sediment-related impacts on the environment. Rational Threshold Values (RTV) quantitative values that can be incorporated into techniques to predict the significance of environmental impacts resulting from military actions -- may be useful for predicting sediment-related impacts.

Objective

The objective of this report is to document the feasibility of using RTVs to predict sediment-related impacts in training areas.

Approach

An extensive survey of previous studies was conducted to determine the effects of sediment on aquatic systems. The effects of sediment on freshwater organisms were summarized (Chapter 2). This information provided a basis for developing potential RTVs for sediment (Chapter 3).

Mode of Technology Transfer

It is recommended that the information in this report be used to develop training area impact prediction techniques. Prediction techniques will be part of a training area maintenance investment program which will be documented in a new technical manual (TM), as well as training area maintenance technologies. The new TM is scheduled for completion in FY86. An interim Engineer Techincal Note on a training area maintenance investment program to control physical degradation will be completed in FY84.

*A key to the references is on p 13. The bibliography (p 15) provides detailed information for each reference.

2 EFFECTS OF SEDIMENT ON FRESHWATER ORGANISMS

Definition of Sediment

The terms suspended solids, sediment, and turbidity are often incorrectly used interchangeably. The term suspended solids is defined as "nonfilterable residue in suspension." It is measured in milligrams of solids per liter (ppm), but is sometimes expressed by measurement of turbidity or light penetration. Sediment is the solid matter component (soil, sand, gravel, and detritus) of suspended solids that has been deposited on the substrate. Synonyms of sediment include alluvium and mud.[2] Turbidity is an optical measurement which describes the degree of opaqueness or alteration of light transmission produced by suspended material and cannot be uniformly equated with concentration.[3]

The organic component (i.e., detritus) of sediment is not considered here, although the organic and inorganic aspects cannot always be easily separated. The literature on the organic component is extensive. Hynes[4] and Wetzel[5] provide discussion and major references on this subject. Further references to sediment, unless otherwise specified, refer to the inorganic component.

Effects on Ecosystems

The concentration of suspended sediment in inland waters is influenced by topography, geology, soil conditions, intensity and duration of rainfall, type and amount of vegetation in the drainage basins, and land use.[6] Lakes, ponds, and reservoirs tend to act as sediment traps.[7] The suspended sediment concentration in most flowing waters varies considerably from day to day, and there may be substantial differences in concentration in different stretches of a stream.[8] Work by Paulet, et al.[9] and Brown[10] provides reviews of sedimentation in lentic* systems.

Sediment alters aquatic environments by screening out light, changing heat radiation, transporting nutrients and toxins, and by blanketing the bottom, causing organic material and other substances to be retained.[11] Suspended sediment scatters and absorbs light, reducing the depth at which effective photosynthesis can occur and altering oxygen relationships.[12] Suspended sediment alters the rate of temperature change in water by absorbing solar radiation so that the

*Inhabiting ponds or swamps.

bottom sediment warms to a lesser extent.[13] In a lentic* system, this may cause or speed up summer stratification.[14]

Adsorption of chemicals by suspended sediment can lead to a buildup of toxic substances in a limited area, especially if a large amount of material is held on the bottom.[15] Erichsen and Kaemmerer[16] and Benoit, et al.[17] described fish kills resulting from such buildups. Toxic substances transport has been reviewed by Sorenson, et al.[18]

Suspended sediment provides a surface for growth of bacteria, fungi, and other microorganisms. Cairns[19] reported that when the presence of particulate matter allows the environment to support much larger populations of these organisms, the dissolved oxygen, pH, and other characteristics of the water are usually changed. Goldman and Kimmel[20] reviewed the literature on the association of microorganisms with suspended sediment particles. They stated that suspended sediment particles can be viewed as exchange surfaces at which both gains (adsorption, colonization, assimilation) and losses (cell lysis, excretion, ingestion, decomposition, leaching) of energy occur continuously, and that such particles constitute a major route of energy flow in lakes and reservoirs.

Sediment absords nutrients, and sediment input may determine the trophic status of an aquatic system.[21] Reviews of sediment-nutrient relationships include Muncy, et al.[22] Sorenson, et al.[23] and Golterman;[24] information on this topic can also be found in any general limnology textbook (for example, Wetzel[25]).

Effects on Algae and Macrophytes

Suspended sediment affects phytoplankton, periphyton, epipelic algae, and macrophyte production. These effects are well documented and easily quantified. Recent references include Edwards,[26] Oschwald,[27] Westlake,[28] Winner,[29] Jones and Bachmann,[30] Stout,[31] and Grobbelaar.[32] Phytoplankton species composition may be influenced indirectly by an altered light regime which changes the water's physico-chemical characteristics.[33] In streams, periphyton and benthic algae can be scoured away by rapidly moving sediment.[34]

Deposition of silt on macrophyte leaves reduces photosynthesis, and some macrophytes may be buried and eliminated by rapid accumulations of silt.[35] Hynes[36] reported that fairly even inputs of sediment in a river can create great stable areas of macrophyte development which can completely alter the substratum and, as a result, the animal population.

Effects on Microinvertebrates and Zooplankton

Although data on the association of microorganisms with suspended sediment are beginning to accumulate,[37] little information is available about sediment effects on non-epipelic forms. If sediment limited primary production because of decreased light transmittance, this would limit the grazing microfauna.[38] In addition, the abrasive action of suspended sediment would be expected to have adverse effects on attached protozoans and micrometazoans.[39] Spoon[40] studied the autwuchs protozoa colonizing artificial substrates in the upper Potomac estuary below a sewage treatment plant. Protozoan abundance increased as turbidity decreased, but as levels of dissolved oxygen, phosphorus, nitrogen, and organic carbons also decreased, the exact role of sediment could not be determined.

The primary impact of sediment on zooplankton is indirect. Increased sediment decreases light; this decreases primary production and therefore food availability.[41] Nutrient regimes altered by silt loads may change species composition either directly or indirectly because of changes in the species composition of the algal food base.[42] Winner[43] observed that filter-feeding cladocerans sank when silt accumulated in their digestive tracts.

Effects on Benthic Macroinvertebrates

Benthic macroinvertebrates usually respond to changes in sediment load by a change in species diversity and/or density. The response in a particular location depends on the existing community's tolerance of and requirements for sediment concentration and particle size distribution. These factors are well documented at the generic level.[44] For example, many stream forms inhabit the interstices between gravel and cobble. Heavy siltation fills in these interstices, eliminating much of this habitat space, and may deplete oxygen in the remaining space.[45] On the other hand, many lentic benthic organisms require fine silt of a certain depth in which to burrow.[46] Prolonged or heavy sedimentation can thus reduce both the total numbers and number of species in an aquatic system and may result in species replacement by forms which are more sediment-tolerant.[47]

Other indirect effects of sediment on benthos which elicit these responses include macrophyte dieoff or increase, and altered food availability.[48]

*Inhabiting ponds or swamps.

Eckblad, et al.[49] reported that increased sedimentation in a river pool allowed *Sagittaria* stands to encroach on the open water. Densities of *Sphaerium* and *Hexagenia* were reduced and subsequently replaced by chronomids, oligochaetes, and gastropods. Allen[50] observed that epipelic diatoms and bluegreen algae in a stream were replaced by filamentous mats when sediment levels increased. This resulted in the replacement of animals adapted to living on exposed surfaces by burrowing and mining forms. Decreases in primary production due to turbidity often reduce macroinvertebrate populations by limiting food.[51]

Sediment may impact benthic populations directly by scouring[52] and smothering.[53] Recent work suggests that drift is a major response of macrobenthos to increased siltation, especially when there are heavy point source inputs.[54]

Suspended sediment can clog bivalve gills, altering pumping and feeding rates, and in some cases causing mortality.[55] Anderson, et al.,[56] described a method for determining LC_{50}'s* for bivalves to sediment.

There is no known information in the literature that describes sediment effects on different larval insect stages, although early instars are probably more susceptible. Davis[57] conducted sediment bioassays using the eggs and larvae of the clam *Mercenaria mercenaria*. Increased sediment concentrations caused increased egg mortality and abnormal embryonic development. Harrison and Farina[58] exposed egg capsules of three species of planorbid snails to varying concentrations of suspended kaolin and sericite and found that cases of abnormal development and mortality increased with increased concentration.

Effects on Fish

Tolerance to suspended and deposited sediment[59] varies among fish species. Some fish are well adapted for life in turbid waters, while others are not.[60] There are many examples in the literature of faunal replacement of silt-intolerant species by silt-tolerant species in aquatic systems following long-term sedimentation and subsequent habitat alteration.[61]

Sediment may impact fish directly by clogging and abrasion of respiratory surfaces, which leads to suffocation, and by smotherings of eggs and larvae. Indirect impacts are more common; they include altering usable habitat and food availability, reducing resistance to disease and parasites, and the effects of sediment-transported toxins and nutrients. The most critical impacts on fish may be those which impair their reproductive processes, adult maturation and reproductive behavior, and egg and larval survival, development, and growth.[62]

Bioassay results indicate that, at normal concentrations, suspended sediment is not acutely lethal to most juvenile and adult fish.[63] Wallen[64] studied 16 species of warmwater fish and noted that most species could withstand concentrations of 20,000 ppm for a week or longer. Fish that succumbed at this concentration showed stress reactions; for example, they floated at the surface and gulped air and displayed reduced 'in and opercular movements. When suspended sediment is directly lethal, mortality results from clogged and damaged gill membranes; this reduces ventilation and leads to suffocation.[65] Such mortality is more pronounced in juveniles.[66] Sherk, et al.,[67] maintain that the more pronounced mortality among juveniles for a given concentration of suspended sediment results because they have a higher oxygen demand per unit body weight and because smaller gills have a greater tendency to sieve and entrap suspended particles, thus inhibiting gaseous exchange.

Muncy, et al.,[68] reviewed the effects of suspended sediment and solids on 120 species of warmwater fish. The fish were cataloged for tolerance/intolerance to suspended sediment during the reproductive period, based on their preferred range as observed in the field. Species which were relatively tolerant were found to be simple spawners, which are defined as: (1) exhibiting little sexual dimorphism in color or distinguishing physical characteristics; (2) not defending territories; (3) not preparing nests; (4) having no behavioral courtship; (5) often spawning at night; and (6) not having parental care. Visual stimuli were not important to the reproductive activities of sediment-tolerant fish (e.g., the carp). However, visual stimuli were important to intolerant species, such as the largemouth bass. These species defended territories, exhibited sexual dimorphism, spawned on harder substrates, built nests, and guarded their nests after spawning.

Sediment can kill eggs through abrasion and physical damage to the chorion; such damage often allows fungal spores to become established[69] and limits gaseous exchange by coating or blanketing the eggs. The latter case has been demonstrated repeatedly for salmonids, both in the laboratory and the field. These

*LC_{50} is the lethal concentration which results in 50 percent mortality for a designated exposure period (usually 24 to 96 hours).

fish require gravel of a certain diameter for spawning.[70] Deposition of fine sediment can clog intergravel interstices; this reduces spawning habitat and reduces the flow of intergravel water and thus the flow of oxygen to the eggs.[71] Sublethal oxygen deprivation may change the length of incubation, reduce size of hatching, and cause developmental abnormalities.[72]

Sediment deposition also increases egg mortality in lentic fishes which lay their eggs on surfaces.[73] Cases of centrarchids shunning or being unable to spawn in turbid areas have been reported.[74]

Hofbauer[75] reported that sediment impeded migration of European barbels but aided European eel migration. Gammon[76] and Reed[77] cited cases of fish emigrating from an area in response to heavy point source sedimentation. Heimstra, et al.,[78] found that turbidity destroyed normal social hierarchies in green sunfish and increased movement of juvenile and adult largemouth bass. Sediment may sweep eggs and larval fish out of their nursery habitat.[79] Larimore[80] noted that smallmouth bass fry experienced a loss of visual orientation under turbid conditions. This also influenced the periodicity and magnitude of larval drift. Geen et al.[81] found that the number of drifting catastomid larvae increased when sediment input increased.

Sediment which blankets or scours stream benthos reduces the availability of these organisms as fish food and thus often reduces fish densities.[82] In lentic systems, turbidity-related reductions in primary production and zooplankton can reduce planktivorous fish.[83]

Sediment can also reduce food availability by making prey less visible to their predators.[84] Vinyard and O'Brien[85] and Gardner[86] reported that turbidity reduces the ability of bluegill to detect zooplankton prey. As a result, fish may consume fewer plankton in a given time than under clear conditions. Bachmann[87] found that slight turbidity increases were detrimental to trout in that they induced them to stop feeding. On the other hand, decreased visibility may be beneficial to some species in that larval fish may escape predation[88] and nonselective feeders can gain a competitive edge.[89]

Food limitations will slow growth, cause developmental abnormalities, and ultimately cause starvation.[90] Hubbs and Whitlock[91] found that as a result of excessive siltation in the Arkansas River, the alimentary canals of young gizzard shad were jammed with inorganic material which contained only a limited amount of plankton. These fish had enlarged heads and underdeveloped tail regions. Buck[92] observed that bass and sunfish grew faster in clear ponds than in turbid ponds. Bulkley[93] reported that high suspended sediment concentrations in a river reduced available food to the extent that fish did not mature and were physically incapable of reproducing.

Suspended sediment may be responsible for reduced disease resistance in some fish.[94] Herbert and Merkins[95] reported increased incidents of finrot in rainbow trout as sediment concentrations increased Cairns[96] noted increased expoparasitism and sloughing off of mucus from fish epithelia exposed to sediment. Some fish kills have been attributed to exposure to sediment which has adsorbed toxic chemicals.[97]

3 POTENTIAL RATIONAL THRESHOLD VALUES

RTVs and Sediment

RTVs having potential application for Army impact analysis should have the following characteristics: (1) can be used by people with little or no practical knowledge of aquatic systems; (2) can be used to measure significant impacts on the higher, more visible trophic levels; (3) are applicable in studies of point source pollution; (4) represent a "yes" or "no" condition (threshold) pertaining to the significance of impact and are quantitative; (5) require minimum data input; and (6) can (and should) be used with output from analytical models. Riggins and Smith[98] outlined numerous potential RTVs for aquatic ecosystems and concluded that two types meet the above criteria: water quality standards and population levels.

Two characteristics of sediment pollution make it difficult for RTVs to measure its impact. First, sediment is not an isolated effect. It can alter light and temperature regimes in aquatic systems, causing changes in oxygen and other chemical characteristics. The organic component of sediment and sediment-transported nutrients and other materials can also alter the chemical regime. Furthermore, colonization of suspended sediment by microorganisms may change the water's chemical characteristics. All of these factors, in addition to the direct effects of sediment, can impact freshwater organisms. Even when analyzing point source situations, detailed chemical analysis of the sediment discharge is necessary, and the researcher must have a thorough knowledge of the physical, chemical, and biological state of the pre-impacted watershed and waterbody.

The second characteristic of sediment pollution is that sediment effects on freshwater organisms, especially in the higher trophic levels, are generally not acute, but occur over long periods of time. For example, sediment is usually not directly toxic to adult fish but impacts populations by altering reproductive fitness (egg and larval survival and condition, adult fecundity and behavior) both directly and through cumulative changes in the food web. Offspring from several successive years could be affected before the impacts would be noticed in the adult population. Therefore, standard bioassays which use adult fish as a basis are not an appropriate information base for potential sediment RTVs. Rather, extensive testing must be carried out to determine the effects of sediment on eggs, larval and juvenile stages, and adults, keeping in mind not only the amount of sediment but also the chemical and physical characteristics.

Sediment affects the entire food web. Generally, the lower trophic levels will be affected before the fish community. Thus, species in the lower trophic levels are the ideal indicator organisms. However, these lower organisms are very hard to identify at the species level, and their life histories are largely unknown. This makes it very hard to quantify the effects of sediment on them. Therefore, fish should probably be used as indicator organisms in lotic* systems. In determining which fish species to use, the researcher should examine the entire community of a particular system and pick several species which have the least tolerance to sediment.

Water Quality Standards

Although local water quality standards should never be exceeded, rigid international and national standards are not desirable, since natural variation in sediment loads and chemical makeup is so great.[99] Furthermore, many standards are rather arbitrarily set and do not incorporate any ecological information.[100] Water quality standards for suspended solids based on the response of the aquatic community, as taken from the literature, have been proposed by the European Inland Fisheries Advisory Commission[101] and adopted by the Committee on Water Quality Criteria in the United States. These are:

	Maximum Concentration Suspended Solids
High level of protection	25 mg/L
Moderate protection	80 mg/L
Low level of protection	400 mg/L
Very low level of protection	>400 mg/L

These standards probably are not supportable for wide-range use, since they are based mainly on information about European coldwater fishes. In addition, the "standard" concentrations are purely volumetric, and do not account for the chemical composition of the solids. Local volumetric water quality standards for sediment could be used for RTVs if they are based on the response of the local aquatic community and are accompanied by a detailed array of other chemical and physical standards, also based on community response. It will be a long time before the desired broad information base is available.

Relative Algal Growth Index: Potential RTV for Lentic Systems

Sediment affects phytoplankton by changing the light and nutrient regimes; these changes affect productivity and species composition. The effects are well-documented in lentic systems. The Relative Algal Growth Index (RAGI) simulates algal growth potential as a function of pre- and post-pollution conditions. The predictive information supplied by RAGI can be used to assess factors that limit growth and to evaluate shifts in the dominance of different algal groups.[103] This model already incorporates many nutrient parameters and can probably be modified for sediment use by adding a light-level component. Research should be conducted to determine if this is true and to test the model.

Fish Population Levels: Potential RTV for Lotic Systems

Sediment affects aquatic systems at the community level; it is therefore an oversimplification to represent single populations of organisms independent of their competitors, predators, and prey. Despite these limitations, population-level simulations can provide information for impact assessment by serving as indicators of stress for critical species (i.e., indicator species chosen on the basis of low sediment tolerance). Population levels can be simulated for almost any organism if survival and fecundity values are known and if the life history has been thoroughly documented. Such information is not available for many aquatic

*Inhabiting rivers and streams.

invertebrates, so the following discussion is limited to fish population levels as a potential RTV.

The most commonly used population simulation is the Leslie matrix.[104] This model describes the density-independent behavior of a single-species population with age-specific fecundity and survival rates and overlapping generations. The number in each age category (x) at a particular time (t) is represented by a column vector. To find the population density (N) at the next time ($t + 1$), the column vector is multiplied by a matrix of age-specific fecundity and survival values.

N_x = number of females alive in age group x to $x + 1$ at time t.

f_x = age-specific fecundity: the number of daughters born in the interval t to $t + 1$ per female alive aged x to $x + 1$, who will be alive in the age group $0 - 1$ at time $t + 1$.

s_x = age-specific survival: the probability that a female of age x (hence, in age group $x - 1$ to x) at time t will be alive with age $x + 1$ at time $t + 1$.

$$A = n \times n \text{ square matrix} = \begin{bmatrix} f_1 & \cdots & f_{n-1} & f_n \\ s_1 & \cdots & 0 & 0 \\ 0 & \cdots & s_{n-1} & 0 \end{bmatrix}$$

N_t and N_{t+1} = column vectors of dimension n which represent the age-specific population structure for t and $t + 1$ time periods.

$$N_{t+1} = A \cdot N_t \text{ or } N_t = A^t N_0$$

Leslie-derived population models have already been proposed and, in some cases, used to assess the effect of power plant operation on fish.[105] These models are all density-independent. One of the main effects of sediment on fish is its impact on the benthic or planktonic populations, which alters fish food availability. When food is limiting, the behavior of a fish population (whether it grows, is stable, or decreases) may depend on the size of the benthic or planktonic populations. Therefore, a density-independent model would not provide a realistic estimate. Density-dependent matrix models have been designed for terrestrial insect, bird, and mammal populations[106] and could probably be modified for use with fish populations. A density-dependent modification of the Leslie matrix proposed by Riggins and Smith[107] is discussed on p 11.

The existing fisheries models are deterministic, which means that given certain initial conditions, they predict one exact outcome.[108] Stochastic models incorporate the effects of chance events on populations and are therefore more biologically realistic. Horst[109] presented a stochastic fish model, but it is density-independent. Density-dependent stochastic versions of the Leslie model have been derived by Niven[110] and Pollard;[111] Sonleitner[112] presented a version which can interface with populations genetics models. Research should be conducted to determine if these models can be modified for impact analysis use.

Most of the fish population models discussed above are set up to evaluate mortality imposed through impingement, entrainment, and heat shock. Jensen[113] described the use of toxicity indices in age-specific population models. Such indices can be used as a database for population models to evaluate point-source sediment pollution in streams. However, the users of a model must always realize that the physical and chemical characteristics of sediment will differ in every area examined; thus, toxicity will have to be tested every time the model is to be used. This testing must be done on all life stages, from egg to reproductively mature adult, and will be a rigorous and time-consuming project.

Once toxicity data are obtained, each f_x and s_x term of the Leslie matrix model can be modified by coefficients representing both the project activities' impacts and their consequences.

$$f'_x = DDF_x \cdot DIF_x \cdot f_x \quad \text{[Eq 1]}$$

and

$$s'_x = DDS_x \cdot DIS_x \cdot s_x \quad \text{[Eq 2]}$$

where DDF_x = density-dependent control coefficient of fecundity of age class x

DIF_x = density-independent control coefficient of fecundity of age class x

DDS_x = density-dependent control coefficient of survivorship of age class x

DIS_x = density-dependent control coefficient of survivorship of age class x

f_x, s_x = natural fecundity and survivorship rates of population in a specified environmental setting.

Then f_x' and s_x' are used as the elements in the projection matrix. The DDS_x and DDF_x terms are functions of population density. DIS_x and DIF_x are functions of sediment impact variables in this case, the age-specific toxicity indices. Toxicity data will not reflect sediment-induced changes in habitat and food-base structure, which may impact the fish population as much, if not more, than direct effects on survival and fecundity. This greatly lowers the model's predictive power. Riggins and Smith[114] have developed a preliminary software package using this model, which incorporates basic physico-chemical environmental setting data into the impact parameters. Research should be done to determine if foodweb information can also be used.

Riggins and Smith[115] presented an example of how quantitative definitions of environmental impacts can be developed from population model output. In Figure 1, pre- and post-impacted population levels ($N_\emptyset(t)$ and $N_p(t)$) have been simulated using the modified matrix model discussed above. Impact magnitude $I(t)$ is measured by comparing the two simulated population levels and is given by the area under the $N_\emptyset(t)$ curve occurring within an appropriate time interval. Population-level impacts are then standardized by calculating the relative impact $RI(t)$, which is the ratio of the shaded area to the corresponding total area. Threshold values can then be placed on $RI(t)$ to designate "significant" impacts, and can be used as RTVs if all of the above-mentioned quantitative ecological information is available.

Riggins and Smith[116] then used the estimated relative impact to estimate population stability (S). Stability is defined as the reciprocal of the impact ($RI(t)$) on the basis of the reasoning that, for a given perturbation, the larger the impact, the smaller the population's stability.

$$S = 1 \Big/ \int_{t=0}^{\infty} (RI(t))^2 \, dt \qquad \text{[Eq 3]}$$

While the relative impact (the denominator of S) ranges from zero (no impact) to one (irreversible loss of species) a reasonable and convenient behavior its reciprocal, S, will range from one to infinity. Thus, S will provide values which would prove awkward to handle, especially when comparing impacts in different areas.

Community Diversity and Stability

Output from the relative algal growth and fish population models will provide information on the general directions and relative magnitudes of impacts rather than actual deterministic predictions of future standing crops. Furthermore, sediment impacts the entire aquatic community, so many effects may be overlooked. Therefore, some type of community analysis should be used as a check to the models discussed above.

One way of doing this is by using diversity indices. Although the predictive power of such indices is low, they could provide valuable information if combined with population simulations. Many different indices are used for pollution assessment, but few are reliable in all situations.[117] Pielou[118] and Peet[119] reviewed many of the indices and provided suggestions for using them in different environmental settings and analyzing different ecological problems.

Riggins and Smith[120] suggested that if the relative impact is simulated for multiple populations at various trophic levels, community stability can be estimated as

$$S_c = 1 \Big/ \frac{1}{M} \sum_{i=1}^{M} W_p(t) \int_{t=0}^{\infty} W_t(t) [RI_i(t)]^2 \, dt \qquad \text{[Eq 4]}$$

where M = number of populations simulated

$W_p(t)$ = weighting function for population

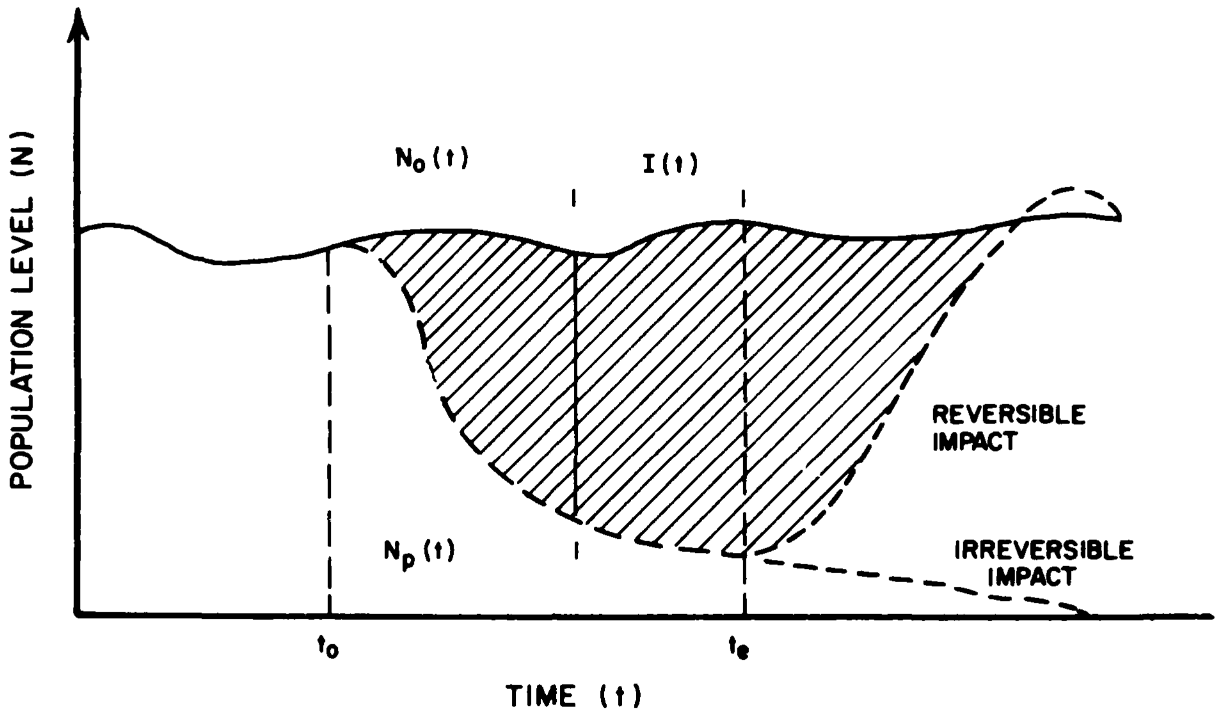
RI_i = relative impact on the population

$W_t(t)$ = weighting function for time period

S_c = community stability

dt = change in time

Here community stability is simply the reciprocal of the mean "total relative impact" averaged over all the species considered, with weighting functions incorporated to allow for quantitative imponderables, such as the role of the species in the ecological web or the rate at which the impact develops. As with population stability (S), S_c will range from one to infinity and would therefore be awkward to use. The "total relative impact" (reciprocal of S_c) is a good theoretical construct. In reality, it would be almost impossible to estimate, because the effects of sediment on the lower trophic levels (e.g., benthic macroinvertebrates) are difficult to quantify, especially with regard to different life stages. There is not yet a sufficient database to conduct sediment-related population simulations using these organisms.



t_o = time at which project activities are initiated

t_e = time at which all project activities have ended

$N_o(t)$ = baseline population simulated with environmental setting and no project activity specifications

$N_p(t)$ = impacted population simulated with environmental setting plus project activity specifications

$I(t)$ = impact at time $t = N_p(t) - N_o(t)$

Figure 1. Pre- and post-impacted population levels based on simulations. (From R. E. Riggins and E. D. Smith, *Aquatic Rational Threshold Value (RTV) Concepts for Army Environmental Impact Assessment*, Technical Report N-74/ADA073032 [U.S. Army Construction Engineering Research Laboratory, 1979.])

Reiger and Henderson[121] presented a model which uses diversity and stability measurements to analyze fish community structure and function. This model is based on the theories of MacArthur[122] and Margalef.[123] The information base required by this model is more rigorous than that required for single-species population simulations or typical diversity indices. Furthermore, the model does not examine the lower trophic levels, and these are the chief concern as a backup to fish simulations. Research at this time would best be directed toward finding ways of incorporating diversity information into RTV procedures. Once this information is obtained, ways of using stability measurements can be examined.

4 CONCLUSIONS

This study investigated the feasibility of using RTVs to predict sediment-related impacts in Army training areas. The research produced the following conclusions:

Local water quality standards may be used as RTVs if they are based on the response of the aquatic community to both physico-chemical and volumetric characteristics of sediment pollution in a specific area.

The RAGI and fish population levels appear to be feasible RTVs to predict sediment-related impact; however, even if used properly, they will not be exact predictors because they examine only a small portion of the community. Therefore, they should only be used with more traditional pollution assessment measurements, such as diversity indices. Further research will incorporate diversity information into the RTV procedures.

The RAGI may prove to be a viable RTV model for lentic systems if the model is modified to include a light-level component.

Fish population levels may be used as RTVs in lotic systems to assess sediment-induced stress on critical species if: (1) the population model used is density-dependent; (2) the model's database includes extensive information on the effects of both the physical and chemical characteristics of the local sediment input on all the life stages of the species in question; and (3) the model incorporates detailed physical, chemical, and biological data on the environmental setting of the species.

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2	4, 91, 180, 238
3	64, 75
4	124
5	272
6	33, 53, 97
7	272
8	33, 115, 163
9	42
10	25
11	70
12	7, 8, 16, 33, 70, 189, 270
13	8, 33
14	32, 272
15	8, 180
16	73
17	20
18	238
19	33
20	90
21	12, 13, 18, 95
22	180
23	238
24	90
25	272
26	67
27	189
28	270, 271
29	281
30	132
31	244
32	95
33	3, 94, 136, 191, 274
34	12, 16, 189, 190
35	66, 67
36	125
37	90
38	189
39	180
40	239, 240
41	29, 50, 189, 244, 272, 281
42	238
43	281

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44	48, 165, 170, 195, 207, 252
45	84, 122, 125
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47	15, 16, 29, 56, 77, 79, 107, 109, 116, 123, 136, 162, 208, 254
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52	12, 18, 29, 51, 186
53	12, 18, 47, 69, 70, 217
54	14, 49, 150, 157, 208, 218
55	33, 70, 44, 148, 213
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59	257
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62	180
63	2, 10, 93, 105, 106, 144, 177, 216, 230, 249, 264
64	264
65	2, 28, 52, 75, 104, 105, 117, 167
66	10, 75, 243
67	229
68	180
69	51, 179, 180, 265
70	17, 131, 169, 200
71	2, 36, 85, 86, 111, 160, 164, 198, 199, 224, 225, 226, 227, 232, 275
72	60, 280
73	10, 43, 103, 177, 179, 265, 283
74	23, 172, 246, 250, 257
75	113
76	83, 84
77	208
78	104
79	51
80	140
81	88
82	51, 81, 107, 109, 217, 219, 242
83	188, 280
84	51, 57, 89, 167, 212, 241, 249
85	262
86	87
87	11
88	61, 212, 248
89	200
90	251
91	120
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93	28
94	74, 180, 238
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97	20, 73
98	211
99	33
100	238
101	74
102	54
103	211
104	145, 146
105	45, 46, 98, 108, 118, 137, 149
106	72, 78, 141, 142, 185, 196, 197, 253, 258, 259
107	211
108	138
109	118, 119,
110	184, 185
111	206
112	237
113	130
114	211
115	211
116	211
117	34, 35, 41, 55, 134, 160, 166, 187, 192, 223, 276, 277, 278
118	201, 202
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Airports and Const. Services Dir.
Ottawa, Ontario, Canada K1A 0N8

National Defense Headquarters
Ottawa, Ontario, Canada K1A 0K2

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